Evaluation of moments of ratios of quadratic forms in normal variables and related statistics

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EVALUATION OF MOMENTS OF RATIOS OF QUADRATIC FORMS IN NORMAL VARIABLES AND RELATED STATISTICS

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ABSTRACT

In this paper we present and describe a subroutine, called QRMOM, which calculates the exact moments of certain functions of ratios of quadratic forms in normal variables. If we let $R = x'Ax/x'Bx$, then QRMOM can calculate,

for $s \geq 1$, $E[R^s]$, $E[R^s(a'x)]$, and $E[R^s(x'Cx)]$,

where x is an nx1 vector of normally distributed variables with some mean μ and a positive definite (hence non-singular) variance-covariance matrix Ω. A, B (positive semi-definite) and C are nxn symmetric matrices and a is an nx1 vector.

The subroutine QRMOM is based on theory developed by Magnus (1986,1989), who showed that these expectations can all be expressed as single integrals and also worked out necessary and sufficient conditions for the existence of expectations in each of the above three cases. QRMOM checks for the existence of a requested s-th moment before carrying out the calculations and if the specified s is too high, it will adjust downwards (if posssible) so that existence of moments is assured.

A diskette containing the Fortran Code of QRMOM and some test programmes is available on request.

Language

Fortran 77

Description and Purpose

The subroutine QRMOM calculates the exact moments of a ratio of two quadratic forms x'Ax and x'Bx and related expectations. Letting R=x'Ax/x'Bx, QRMOM can handle the following three cases:

(1) $E\left[R^s \right]$ $s \geq 1$

(2) $E\left[R^s (a'x) \right]$ $s \geq 1$

(3) $E\left[R^s (x'Cx) \right]$ $s \geq 1.$

Here x is an nx1 vector of normally distributed variables with some mean μ and a positive definite (hence non-singular) variance-covariance matrix Ω. A, B (positive semi-definite) and C are nxn symmetric matrices and a is an nx1 vector. In case (2) when μ=0 a simple symmetry argument shows that the expectation vanishes if it exists. QRMOM does not calculate the expectation in that case, but simply sets it equal to zero.

The above calculations are required in a variety of situations when econometric or time series estimators take the form of a ratio of quadratic forms in normal variables. The calculation of moments, forecast bias or mean-square forecast error relating to such estimators will involve the evaluation of expectations of the form (1), (2) or (3). Examples are provided by the estimation of an AR(1) process with or without an intercept, stationary or non-stationary. See for example Hoque, Magnus and Pesaran (1988) and Magnus and Pesaran (1988, 1989).

The subroutine QRMOM is based on theory developed by Magnus(1986,1989), who showed that these expectations can all be expressed as single integrals and also worked out necessary and sufficient conditions for the existence of expectations in each of the above three cases. QRMOM checks for the existence of a requested s-th moment before carrying out the calculations and if the specified s is too high, it will adjust s downwards (if possible) so that existence of moments is assured.

Parameter statements

The following parameters have been set in subroutines QRMOM and PARINT and function F:

NDIM=50	The dimension of various work spaces. NDIM≥n where n is the number of observations.
ISPAR=77 & ISDIM=12	The dimensions of the array ISPRTN (ISPARxISDIM) where all possible partitions for a particular s are stored. This two dimensional array is set up by subroutine PARINT.
MAXMOM=24	The maximum of s allowed.

If n>50 is to be specified, the relevant parameter statements for NDIM should be increased accordingly.

If 12<s≤24 is to be calculated, then both ISPAR and ISDIM should be increased.

Working out expectations for s>24 is possible. In that case not only ISPAR and ISDIM should be changed in the parameter statements, but also MAXMOM. Furthermore, the DATA statement in subroutine PARINT should be extended to include MAXMOM numbers. In the data statement the vector NUM has been set up to contain the number of all possible partitions of numbers up to 24. If a MAXMOM bigger than 24 is specified, the data statement for NUM should be extended accordingly. For a table containing the partitions for integers up to 100 see Hall(1986, p.38).

Common statements

Since the NAG routine D01AMF for the evaluation of the integral requires the function F(x) to have only one argument, the other arguments needed in the calculation of F(x) are passed through two labelled common areas QRREAL and QRINT.

Structure

SUBROUTINE QRMOM(ICASE, NOBS, IS1, IS2, A, B, C, ELA, IEMU, EMU, IOMEGA, OMEGA, ITEM, ISMAX, RESULT, ABSERR, IFAIL)

Formal Parameters

ICASE	integer	input:	1, 2 or 3 corresponding to (1), (2) or (3) above.
NOBS	integer	input:	No of observations n
IS1	integer	input:	order of the lowest moment required.
		output:	unchanged unless IS1 ≤0 in which case IS1 is set equal to one.
IS2	integer	input:	order of the highest moment required.
		output:	unchanged unless IS2>M where M=MIN(ISMAX,MAXMOM,ISDIM) in which case IS2 is set equal to M.
A	real array of dimension at least NOBSx(NOBS+1)/2	input:	symmetric matrix in (1), (2) or (3). Only the lower part of A is stored as $a_{11}, a_{21}, a_{22}, a_{31}, a_{32}, a_{33}$ etc.
B	real array of dimension at least NOBSx(NOBS+1)/2	input:	symmetric positive semidefinite matrix B in (1), (2) or (3). Only the lower part of B is stored.
C	real array of dimension at least NOBSx(NOBS+1)/2	input:	symmetric matrix C in (3). Only the lower part of C stored. No need to assign values to C in cases (1) and (2) though storage should be allocated to it.
ELA	real array of dimension at least NOBS	input:	a in (2). No need to assign values to a in cases (1) and (3) though storage should be allocated to it.

IEMU	integer	input:	$=0$ if $\mu=0$ $\neq 0$ if $\mu\neq 0$
EMU	real array of dimension at least NOBS	input:	vector μ. Values required only if IEMU≠0 though storage should be allocated to it.
IOMEGA	integer	input:	= -1 if L^{-1} is supplied where $\Omega = LL'$, L lower triangular = 1 if L is supplied where $\Omega = LL'$, L lower triangular = 2 if Ω is supplied
OMEGA	real array of dimension at least NOBSx(NOBS+1)/2	input:	either L or L^{-1} or Ω where only lower part of these are stored
ITEM	integer	output:	if ICASE=1, ITEM indicates which condition in Theorem 1 of Magnus(1989) holds ie 1≤ITEM≤3 if ICASE=2, ITEM indicates which condition in Theorem 2 of Magnus(1989) holds ie 1≤ITEM≤5 if ICASE=3, ITEM indicates which condition in Theorem 3 of Magnus(1989) holds ie 1≤ITEM≤7
ISMAX	integer	output:	the maximum of s in (1), (2) or (3) for which these expectations exist. ISMAX=100 indicates that the expectation exists for every s.
RESULT	real array of dimension at least IS2-IS1+1	output:	the required expectations stored as: RESULT(1)=IS1-th moment RESULT(2)=(IS1+1)th moment ...... RESULT(IS2-IS1+1)=IS2-th moment
ABSERR	real array of dimension at least IS2-IS1+1	output:	the absolute error in calculating each of the expectations. Stored as RESULT.

IFAIL	integer	output:	a fault indicator where:

0: no error
1: NOBS > NDIM or NOBS ≤ 1
2: ICASE out of range
3: IOMEGA out of range
4: Eigenvalues of B could not be calculated
5: B is not pos. semi-definite
6: B is the null matrix
7: if IOMEGA=2 Ω not pos. definite

if IOMEGA=1 diagonal elements of L not all positive

if IOMEGA=-1 diagonal elements of L^{-1} not all positive

8: if IOMEGA=2 or 1, L can't be inverted

if IOMEGA=-1, L^{-1} can't be inverted
9: eigenvalues of L'BL could not be calculated

10: L'BL is not pos. semidefinite
11: L'BL is the null matrix
12: IS1>IS2 or moments in the adjusted range do not exist or ISDIM in the parameter statement is too small

13: ISPAR in the parameter statement is too small

14-19:
error in calculating the integral corresponding to IFAIL=1 to 6 in the NAG library routine D01AMF

Auxiliary Algorithms

QRMOM uses two routines from the NAG library, namely F02ABF (calculation of eigenvalues and eigenvectors of a real symmetric matrix) and D01AMF (evaluation of a single integral). F02ABF is called by subroutine EVALUE and D01AMF is called by subroutine INTGRL. Users who wish not to use these two NAG library routines can substitute their own versions of subroutines EVALUE and INTGRL.

In addition to subroutines EVALUE and INTGRL, QRMOM calls various functions and subroutines:

(F1)	REAL*8 FUNCTION F(X):	used in calculating the integral
(F2)	FUNCTION INX(I,J):	picks out the appropriate element of a symmetric matrix stored in lower triangular form
(F3)	FUNCTION NFACT(N):	calculates N!
(S1)	SUBROUTINE POWER:	called by F(X)
(S2)	SUBROUTINE CALCRA:	called by F(X)
(S3)	SUBROUTINE INIT:	initializes all matrices and vectors and checks for the existence of expectations
(S4)	SUBROUTINE EXIST:	called by INIT
(S5)	SUBROUTINE PARINT:	constructs the matrix containing all partitions of an integer
(S6)	SUBROUTINE SEP:	decomposes A (pos. def.) into LL' (L lower triangular) and replaces A by L

(S7) SUBROUTINE LOWINV: inversion (in place) of a lower triangular matrix

(S8) SUBROUTINE MULT1: computes C=B'AB (A symmetric, B lower triangular)

(S9) SUBROUTINE MULT2: computes C=B'AB (A symmetric)

(S10) SUBROUTINE NULL1: checks to see if AB=0 (A symmetric)

(S11) SUBROUTINE NULL2: checks to see if B'AB=0 (A symmetric)

Constants

The DATA statement in QRMOM sets EPS = 1.0-11 as a small number. Any number with an absolute value below EPS will be treated as zero.

Precision

The version of the routines listed below is in double precision (Real*8). In order to change the program to single precision the following changes should be made:

(1) Change all IMPLICIT REAL*8 to IMPLICIT REAL*4

(2) Change the constants in the DATA statements to single precision versions.

(3) Change DSQRT, DABS, DEXP to SQRT, ABS, EXP in the statement functions appearing in the beginning of routines F, EXIST, SEP, LOWINV, NULL1, NULL2.

Time

In order to work out the relationship between the CPU time and n and s we did some calculations on the VAX 6330 at the London School of Economics for different combinations of s (1 to 8) and n(10,20,30,40 & 50). In Table 1 the results of regressions of LOG(CPU) as a function of n and s for different values of ICASE and IEMU are reported. These regressions enable us to estimate the absolute CPU time (in seconds) for different combinations of n, s, ICASE and IEMU. Furthermore, if we differentiate the regression equations with respect to n or s we should be able to work out the % increase in CPU time as a result of an increase in n or s. For example if we differentiate the regression equation for ICASE=1 and IEMU=0 with respect to s we have

$$\frac{\partial \log(CPU)}{\partial s} = 2.172 + .003868*n - 2*.3701*s - 2*.0005736*n*s + 3*.0229*s^2.$$

In particular, when n=40 and s=4, we obtain

$$\frac{\partial \log(CPU)}{\partial s} = .2816.$$

This implies a growth in CPU time of about 28.2%. This should be compared with an increase in actual CPU time on the VAX from 380.2 seconds to 500.4 seconds which implies an increase of 31.6%. Hence using the relationships summarized in Table 1, once the timing of a particular combination of ICASE, IEMU, n and s is known, we can work out the marginal increase in CPU time. We estimate that the error in estimating the percentage change in CPU time is less than 15%.

Table 1. Results of least-squares regressions of LOG(CPU) as a function of n and s for different values of ICASE and IEMU

	ICASE=1 IEMU=0	ICASE=1 IEMU=1	ICASE=2 IEMU=1	ICASE=3 IEMU=0	ICASE=3 IEMU=1
Constant	-4.9046	-4.6367	-4.5340	-4.5108	-3.5408
n	0.2946	0.2967	0.3191	0.3182	0.2827
s	2.1720	2.0809	1.8911	1.8457	1.6686
n^2	-0.004397	-0.004623	-0.005783	-0.004956	-0.004182
ns	0.003868	0.004229	0.0070239	-	-
s^2	-0.3701	-0.3565	-0.3135	-0.2963	-0.2578
n^3	0.0000272	0.0000299	0.0000459	0.0000319	0.0000248
n^2s	-	-	-0.0000981	0.0000532	0.0000838
ns^2	-0.0005736	-0.0005799	-	-0.000583	-0.0008435
s^3	0.0229	0.0222	0.0176	0.0185	0.0167
$\bar{R}^2$	0.9951	0.9959	0.9957	0.9964	0.9960
SE of reg.	0.1393	0.1248	0.1302	0.1171	0.1169

Accuracy

The data statement in QRMOM sets ESPABS=1.0-5 (absolute error) and EPSREL=1.00-4 (relative error) in the calculation of the integrals. These can be changed in order to achieve different levels of accuracy.

In order to check the accuracy of calculations we used QRMOM to evaluate the first 4 moments of the F distribution with 4 and 16 degrees of freedom. This was achieved by using an arbitrary (20x4) matrix R and by setting $A=R(R'R)^{-1}R'$,B=I-A and Ω=I. Setting ICASE=1 and IEMU=0 the first 4 moments of x'Ax/x'Bx were calculated. Since

$$F_{4,16} = 4(x'Ax/x'Bx),$$

we obtain

$$\mu'_s=E(F_{4,16})^s= 4^s\ E(x'Ax/x'Bx)^s.$$

The exact values for μ'_s can be calculated using the formula in Kendall and Stuart(1977, exercise 16.1 p. 423), which implies

$$(4)\qquad E(x'Ax/x'Bx)^s= \frac{\Gamma(2+s)\ \Gamma(8-s)}{\Gamma(2)\ \Gamma(8)}.$$

Table 2 allows the comparison between the exact results using (4) and the calculated values using QRMOM for s=1 to 4.

Table 2. Accuracy of moments of an F distribution calculated by QRMOM

s	Exact	Calculated
1	2/7	0.28571429
2	1/7	0.14285714
3	4/35	0.11428571
4	1/7	0.14285714

Examining Table 2 shows that in this example an accuracy of at least eight decimal points is achieved.

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```
      SUBROUTINE QRMOM(ICASE,NOBS,IS1,IS2,A,B,C,ELA,IEMU,EMU,
     +IOMEGA,OMEGA,ITEM,ISMAX,RESULT,ABSERR,IFAIL)
C
C       ALGORITHM AS??? APPL. STATIST. (1990)
C       WORKS OUT IS1-TH TO IS2-TH MOMENTS RELATING TO
C       RATIOS OF QUADRATIC FORMS IN NORMAL VARIABLES
C
      IMPLICIT REAL*8(A-H,O-Z)
      PARAMETER(NDIM=50,ISDIM=12,ISPAR=77,MAXMOM=24)
      PARAMETER(NSYM=NDIM*(NDIM+1)/2)
      DIMENSION A(*),B(*),C(*),ELA(*),EMU(*),OMEGA(*),
     +RESULT(*),ABSERR(*)
      DIMENSION WMAT1(NDIM,NDIM),WMAT2(NDIM,NDIM),WORK(NSYM)
      DIMENSION WGRL(2000),IWGRL(252)
      COMMON/QRINT/ICODE,IMU,N,IS,ISROW,ISPRTN(ISPAR,ISDIM)
      COMMON/QRREAL/RLANDA(NDIM),SMU(NDIM),SLA(NDIM),
     +AA(NSYM),CC(NSYM)
      EXTERNAL F
      DATA ZERO,ONE,EPS,INF/0.0D0,1.0D0,1.D-11,100/
      DATA EPSABS,EPSREL/1.D-05,1.D-04/
      IFAIL=0
      ICODE=ICASE
      IMU=IEMU
      IOM=IOMEGA
      N=NOBS
C
C       CHECK THE EXISTENCE OF EXPECTATIONS AND
C       INITIALIZE ALL MATRICES AND VECTORS
C
      CALL INIT(ICODE,N,NDIM,A,B,C,ELA,IMU,EMU,
     +IOM,OMEGA,AA,RLANDA,CC,SLA,SMU,WMAT1,WMAT2,WORK,
     +ITEM,ISMAX,ZERO,ONE,EPS,INF,IFAIL)
      IF(IFAIL.NE.0) RETURN
```

```
      IFAIL=12
      IF(IS1.GT.IS2) RETURN
      IS1=MAX(IS1,1)
      IS2=MIN(IS2,ISMAX,MAXMOM,ISDIM)
      IF(IS1.GT.IS2) RETURN
C
C         WORK OUT IS1-TH TO IS2-TH MOMENTS
C
      DO 1000 IS=IS1,IS2
C
C         WORK OUT ALL PARTITIONS OF IS
C
      CALL PARINT(IS,ISPRTN,ISPAR,ISDIM,ISROW,IFAIL)
      IFAIL=IFAIL+11
      IF(IFAIL.NE.11) RETURN
C
C         CALCULATE THE IS-TH MOMENT AS AN INTEGRAL
C
      CALL INTGRL(F,ZERO,EPSABS,EPSREL,RES,ABSE,
     +WGRL,IWGRL,IFAIL)
      IFAIL=IFAIL+13
      IF(IFAIL.NE.13) RETURN
      FACT=NFACT(IS-1)
C
C         STORE RESULTS
C
      RESULT(IS-IS1+1)=RES/FACT
      ABSERR(IS-IS1+1)=ABSE/FACT
1000  CONTINUE
      IFAIL=0
      RETURN
      END
```

```
      REAL*8 FUNCTION F(X)
C
C       EVALUATION OF F AS A FUNCTION OF X
C       USED IN THE CALCULATION OF THE INTEGRAL
C
C       NOTE: ALL OTHER ARGUMENTS OF F ARE IN
C             COMMONS QRINT AND QRREAL
C
      IMPLICIT REAL*8(A-H,O-Z)
      PARAMETER(NDIM=50,ISDIM=12,ISPAR=77)
      PARAMETER(NSYM=NDIM*(NDIM+1)/2)
      PARAMETER(ISSYM=ISDIM*(ISDIM+1)/2)
      COMMON/QRINT/ICODE,IMU,N,IS,ISROW,ISPRTN(ISPAR,ISDIM)
      COMMON/QRREAL/RLANDA(NDIM),SMU(NDIM),SLA(NDIM),
     +AA(NSYM),CC(NSYM)
      DIMENSION VLA(NDIM),VMU(NDIM),R(NSYM),GAMMA(NSYM),
     +WORK1(NSYM),WORK2(NSYM),PP(ISSYM),POW(NDIM,ISDIM),
     +TR1(ISDIM),TR2(ISDIM),OUT(3),NK(ISDIM)
      DATA ZERO,HALF,ONE,TWO,FOUR/0.0D0,0.5D0,1.0D0,2.0D0,4.0D0/
      ZSQRT(H)=DSQRT(H)
      ZEXP(H)=DEXP(H)
      F1=X**(IS-1)
      F2=ONE
      TRACE=ZERO
      DO 10 I=1,N
      SPI=ONE+TWO*X*RLANDA(I)
      SPI=ONE/ZSQRT(SPI)
      F2=F2*SPI
      IF(IMU.NE.0) VMU(I)=SMU(I)*SPI
      IF(ICODE.EQ.2) VLA(I)=SLA(I)*SPI
      DO 10 J=1,I
      SPJ=ONE+TWO*X*RLANDA(J)
      SPJ=ONE/ZSQRT(SPJ)
      SP=SPI*SPJ
```

```
      IJ=INX(I,J)
      R(IJ)=AA(IJ)*SP
      IF(ICODE.EQ.3) THEN
        GAMMA(IJ)=CC(IJ)*SP
        IF(I.EQ.J) TRACE=TRACE+GAMMA(IJ)
      END IF
10    CONTINUE
      F3=ONE
      IF(IMU.NE.0) THEN
        F3=ZERO
        DO 20 J=1,N
        SP=SMU(J)*SMU(J)-VMU(J)*VMU(J)
20      F3=F3+SP
        F3=ZEXP(-HALF*F3)
      END IF
      CALL POWER(ICODE,IMU,R,GAMMA,VMU,TR1,TR2,
     +POW,WORK1,WORK2,N,NDIM,IS,ZERO,ONE,TWO)
      IF(IMU.NE.0) THEN
        IF(ICODE.NE.1) THEN
          SUM=ZERO
          DO 40 I=1,N
          IF(ICODE.EQ.2) THEN
            SUM=SUM+VLA(I)*VMU(I)
          ELSE IF(ICODE.EQ.3) THEN
            TT=TWO
            DO 30 J=1,I
            IF(I.EQ.J) TT=ONE
30          SUM=SUM+TT*VMU(I)*GAMMA(INX(I,J))*VMU(J)
          END IF
40        CONTINUE
          TRACE=TRACE+SUM
        END IF
        DO 70 L=1,IS
        RL=L
```

```
          SUM1=ZERO
          SUM2=ZERO
          DO 60 I=1,N
          RP=POW(I,L)
          SUM1=SUM1+VMU(I)*RP
          IF(ICODE.EQ.2) THEN
            SUM2=SUM2+VLA(I)*RP
          ELSE IF(ICODE.EQ.3) THEN
            DO 50 J=1,N
50          SUM2=SUM2+RP*GAMMA(INX(I,J))*VMU(J)
          END IF
60        CONTINUE
          TR1(L)=TR1(L)+RL*SUM1
          IF(ICODE.EQ.2) THEN
            TR2(L)=SUM2
          ELSE IF(ICODE.EQ.3) THEN
            TR2(L)=TR2(L)+TWO*SUM2
          END IF
70        CONTINUE
          IF(ICODE.EQ.3) CALL MULT2(GAMMA,POW,PP,N,IS,NDIM,ZERO)
        END IF
        F4=ZERO
        DO 90 I=1,ISROW
        IB=1
        DO 80 L=1,IS
        K=ISPRTN(I,L)
        NK(L)=K
        IF(K.NE.0)IB=IB*NFACT(K)*((2*L)**K)
80      CONTINUE
        IB=(NFACT(IS)*(2**IS))/IB
        RB=IB
        LCODE=ICODE
        IF(ICODE.EQ.2.AND.IMU.EQ.0) LCODE=0
        IF(ICODE.EQ.3.AND.IMU.EQ.0) LCODE=2
```

```
      IF(LCODE.NE.0) CALL CALCRA(LCODE,IS,NK,TR1,TR2,PP,OUT,ZERO,
     +ONE,TWO)
      IF(LCODE.EQ.0) THEN
        RA=ZERO
      ELSE IF(LCODE.EQ.1) THEN
        RA=OUT(1)
      ELSE IF(LCODE.EQ.2) THEN
        RA=OUT(1)*TRACE+TWO*OUT(2)
      ELSE IF(LCODE.EQ.3) THEN
        RA=OUT(1)*TRACE+TWO*OUT(2)+FOUR*OUT(3)
      END IF
      F4=F4+RA*RB
90    CONTINUE
      F=F1*F2*F3*F4
      RETURN
      END

      SUBROUTINE POWER(ICODE,IMU,R,GAMMA,VMU,TR1,TR2,POW,
     +WORK1,WORK2,N,NDIM,IS,ZERO,ONE,TWO)
C
C       CALLED BY FUNCTION F(X)
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION R(*),GAMMA(*),WORK1(*),WORK2(*)
      DIMENSION VMU(*),TR1(*),TR2(*)
      DIMENSION POW(NDIM,*)
      NN=N*(N+1)/2
      DO 90 L=1,IS
      IF(L.EQ.1) THEN
        DO 10 I=1,NN
10      WORK1(I)=R(I)
      ELSE
        DO 30 I=1,N
        DO 30 J=1,I
```

```
        IJ=INX(I,J)
        SUM=ZERO
        DO 20 K=1,N
        IK=INX(I,K)
        KJ=INX(K,J)
20      SUM=SUM+R(IK)*WORK1(KJ)
30      WORK2(IJ)=SUM
        DO 40 I=1,NN
40      WORK1(I)=WORK2(I)
      END IF
      SUM=ZERO
      DO 50 I=1,N
      RI=WORK1(INX(I,I))
50    SUM=SUM+RI
      TR1(L)=SUM
      IF(IMU.NE.0) THEN
        DO 70 I=1,N
        SUM=ZERO
        DO 60 J=1,N
        WW=WORK1(INX(I,J))
60      SUM=SUM+WW*VMU(J)
70      POW(I,L)=SUM
      END IF
      IF(ICODE.EQ.3) THEN
        SUM=ZERO
        DO 80 I=1,N
        TT=TWO
        DO 80 J=1,I
        IJ=INX(I,J)
        WW=WORK1(IJ)
        IF(I.EQ.J) TT=ONE
80      SUM=SUM+TT*WW*GAMMA(IJ)
        TR2(L)=SUM
      END IF
90    CONTINUE
      RETURN
      END
```

```
      SUBROUTINE CALCRA(LCODE,IS,NK,TR1,TR2,PP,OUT,ZERO,ONE,TWO)
C
C       CALLED BY FUNCTION F(X)
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION NK(*),TR1(*),TR2(*),PP(*),OUT(*)
      PR=ONE
      DO 10 J=1,IS
      NJ=NK(J)
10    IF(NJ.NE.0) PR=PR*(TR1(J)**NJ)
      OUT(1)=PR
      IF(LCODE.EQ.1) RETURN
      SUM=ZERO
      SUM1=ZERO
      DO 60 J=1,IS
      RJ=J
      NJ=NK(J)
      RNJ=NJ
      PR=ONE
      DO 20 L=1,IS
      NL=NK(L)
      IF(L.EQ.J) NL=NL-1
20    IF(NL.GT.0)PR=PR*(TR1(L)**NL)
      IF(NJ.NE.0) SUM=SUM+RJ*RNJ*PR*TR2(J)
      IF(LCODE.EQ.2) GO TO 60
      PR=ONE
      DO 30 L=1,IS
      NL=NK(L)
      IF(L.EQ.J) NL=NL-2
30    IF(NL.GT.0) PR=PR*(TR1(L)**NL)
      IF(NJ.GT.1) SUM1=SUM1+RJ*RJ*RNJ*(RNJ-ONE)*PR*PP(INX(J,J))
      IF(J.GT.1) THEN
        DO 50 I=1,J-1
```

```
          RI=I
          NI=NK(I)
          RNI=NI
          PR=ONE
          DO 40 L=1,IS
          NL=NK(L)
          IF(L.EQ.I.OR.L.EQ.J) NL=NL-1
40        IF(NL.GT.0) PR=PR*(TR1(L)**NL)
50        IF(NI.GT.0.AND.NJ.GT.0)
     +     SUM1=SUM1+TWO*RI*RJ*RNI*RNJ*PR*PP(INX(I,J))
      END IF
60    CONTINUE
      OUT(2)=SUM
      OUT(3)=SUM1
      RETURN
      END

      SUBROUTINE INIT(ICODE,N,NDIM,A,B,C,ELA,IMU,EMU,
     +IOM,OMEGA,AA,RLANDA,CC,SLA,SMU,WMAT,PMAT,WORK,
     +ITEM,IMAX,ZERO,ONE,EPS,INF,IFAIL)
C
C        INITIALIZES ALL MATRICES AND VECTORS AND CHECKS
C        FOR THE EXISTENCE OF EXPECTATIONS
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(*),B(*),C(*),OMEGA(*),AA(*),CC(*),WORK(*)
      DIMENSION ELA(*),EMU(*),SLA(*),SMU(*),RLANDA(*)
      DIMENSION WMAT(NDIM,*),PMAT(NDIM,*)
      IFAIL=1
      IF(N.GT.NDIM.OR.N.LE.1) RETURN
      IFAIL=2
      IF(ICODE.LT.1.OR.ICODE.GT.3) RETURN
      IFAIL=3
      IF(IOM.NE.-1.AND.IOM.NE.1.AND.IOM.NE.2) RETURN
```

```
      CALL EVALUE(B,NDIM,N,RLANDA,PMAT,WMAT,CC,EPS,IRANK,ZERO,IFAIL)
      IFAIL=IFAIL+3
      IF(IFAIL.NE.3) RETURN
      IFAIL=6
      IF(IRANK.EQ.0) RETURN
      CALL EXIST(ICODE,N,NDIM,A,C,ELA,PMAT,IRANK,
     +ITEM,IMAX,ZERO,EPS,INF)
      DO 10 I=1,N
      DO 10 J=1,I
      IJ=INX(I,J)
10    CC(IJ)=OMEGA(IJ)
      IF(IOM.EQ.1.OR.IOM.EQ.-1) THEN
        IFAIL=7
        DO 20 I=1,N
        R=CC(INX(I,I))
        IF(R.LT.EPS) RETURN
20      CONTINUE
      END IF
      IFAIL=0
      IF(IOM.EQ.2) CALL SEP(CC,N,ONE,EPS,IFAIL)
      IF(IOM.EQ.-1) CALL LOWINV(CC,N,ZERO,ONE,EPS,IFAIL)
      IF(IFAIL.NE.0) THEN
        IF(IOM.EQ.2) IFAIL=7
        IF(IOM.EQ.-1) IFAIL=8
        RETURN
      END IF
      CALL MULT1(B,CC,AA,N,ZERO)
      CALL EVALUE(AA,NDIM,N,RLANDA,PMAT,WMAT,WORK,EPS,IRANK,ZERO,IFAIL)
      IFAIL=IFAIL+8
      IF(IFAIL.NE.8)RETURN
      IFAIL=11
      IF(IRANK.EQ.0) RETURN
      DO 40 I=1,N
      DO 40 J=1,N
```

```
      SUM=ZERO
      DO 30 K=1,I
30    SUM=SUM+CC(INX(I,K))*PMAT(K,J)
40    WMAT(I,J)=SUM
      CALL MULT2(A,WMAT,AA,N,N,NDIM,ZERO)
      IF(IMU.NE.0) THEN
        IF(IOM.GT.0) THEN
          CALL LOWINV(CC,N,ZERO,ONE,EPS,IFAIL)
          IFAIL=IFAIL+7
          IF(IFAIL.NE.7) RETURN
        END IF
        DO 60 I=1,N
        SUM=ZERO
        DO 50 J=1,N
        DO 50 K=1,J
        IF(IOM.GT.0) SUM=SUM+PMAT(J,I)*CC(INX(J,K))*EMU(K)
        IF(IOM.EQ.-1) SUM=SUM+PMAT(J,I)*OMEGA(INX(J,K))*EMU(K)
50      CONTINUE
60      SMU(I)=SUM
      END IF
      IF(ICODE.EQ.2) THEN
        DO 80 I=1,N
        SUM=ZERO
        DO 70 J=1,N
70      SUM=SUM+WMAT(J,I)*ELA(J)
80      SLA(I)=SUM
      ELSE IF(ICODE.EQ.3) THEN
        CALL MULT2(C,WMAT,CC,N,N,NDIM,ZERO)
      END IF
      IFAIL=0
      RETURN
      END
```

```
      SUBROUTINE EXIST(ICODE,N,NDIM,A,C,ELA,Q,IRANK,
     +ITEM,IMAX,ZERO,EPS,INF)
C
C       CHECKS THE EXISTENCE OF THE EXPECTATION TO BE CALCULATED
C       USING THEOREMS 1-3 OF MAGNUS(1989)
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(*),C(*),ELA(*),Q(NDIM,*)
      ZABS(H)=DABS(H)
      ITEM=1
      IMAX=INF
      IF(IRANK.EQ.N) RETURN
      IZERO=N-IRANK
C ... CHECK TO SEE IF A*Q IS ZERO
      CALL NULL1(A,Q,N,IZERO,NDIM,ZERO,EPS,IX1)
      IF(IX1.EQ.0) RETURN
C ... CHECK TO SEE IF Q'*A*Q IS ZERO
      CALL NULL2(A,Q,N,IZERO,NDIM,ZERO,EPS,IX1)
      IF(ICODE.EQ.1) THEN
        IF(IX1.EQ.0) THEN
          IMAX=IRANK-1
          ITEM=2
        ELSE IF(IX1.EQ.1) THEN
          IMAX=(IRANK-1)/2
          ITEM=3
        END IF
      ELSE IF(ICODE.EQ.2) THEN
C ...   CHECK TO SEE IF Q'*ELA IS ZERO
        IX2=1
        DO 20 K=1,IZERO
        SUM=ZERO
        DO 10 J=1,N
10      SUM=SUM+Q(J,K)*ELA(J)
        IF(ZABS(SUM).GT.EPS) GO TO 30
```

```
20        CONTINUE
          IX2=0
30        CONTINUE
          IF(IX1.EQ.0.AND.IX2.EQ.0) THEN
            IMAX=IRANK
            ITEM=2
          ELSE IF(IX1.EQ.0.AND.IX2.EQ.1) THEN
            IMAX=IRANK-1
            ITEM=3
          ELSE IF(IX1.EQ.1.AND.IX2.EQ.0) THEN
            IMAX=IRANK/2
            ITEM=4
          ELSE
            IMAX=(IRANK-1)/2
            ITEM=5
          END IF
        ELSE IF(ICODE.EQ.3) THEN
C ...     CHECK TO SEE IF C*Q IS ZERO
          CALL NULL1(C,Q,N,IZERO,NDIM,ZERO,EPS,IX2)
C ...     CHECK TO SEE IF Q'*C*Q IS ZERO
          CALL NULL2(C,Q,N,IZERO,NDIM,ZERO,EPS,IX3)
          IF(IX1.EQ.0) THEN
            IF(IX2.EQ.0) THEN
              IMAX=IRANK+1
              ITEM=2
            ELSE IF(IX2.EQ.1.AND.IX3.EQ.0) THEN
              IMAX=IRANK
              ITEM=3
            ELSE IF(IX3.EQ.1) THEN
              IMAX=IRANK-1
              ITEM=4
            END IF
          ELSE IF(IX1.EQ.1) THEN
            IF(IX2.EQ.0) THEN
```

```
          IMAX=(IRANK+1)/2
          ITEM=5
        ELSE IF(IX2.EQ.1.AND.IX3.EQ.0) THEN
          IMAX=IRANK/2
          ITEM=6
        ELSE IF(IX3.EQ.1) THEN
          IMAX=(IRANK-1)/2
          ITEM=7
        END IF
      END IF
    END IF
    RETURN
    END

    SUBROUTINE PARINT(M,MPRTN,MRDIM,MDIM,MR,IFAIL)
C
C        CONSTRUCTS THE MR X M MATRIX "MPRTN" CONTAINING
C        ALL MR PARTITIONS OF THE INTEGER M
C
    PARAMETER(MAXMOM=24)
    DIMENSION MPRTN(MRDIM,MDIM)
    DIMENSION NUM(MAXMOM),IWORK(MAXMOM)
    DATA NUM/1,2,3,5,7,11,15,22,30,42,56,77,101,135,176,231,
   +297,385,490,627,792,1002,1255,1575/
    IFAIL=1
    IF(M.LT.1.OR.M.GT.MAXMOM.OR.M.GT.MDIM) RETURN
    IFAIL=2
    IF(NUM(M).GT.MRDIM) RETURN
    IFAIL=0
    N1=0
    N2=1
    N3=0
    MR=1
    M1=1
```

```
      L=0
      MPRTN(1,1)=1
      IF(M.EQ.1) RETURN
      DO 10 J=2,M
10    MPRTN(1,J)=0
      DO 99 K=2,M
      IF(N2.NE.0) THEN
        DO 30 I=1,N2
        MPRTN(MR+I,1)=0
        DO 20 J=2,M
20      MPRTN(MR+I,J)=MPRTN(I+N1,J)
30      MPRTN(MR+I,2)=MPRTN(MR+I,2)+1
      END IF
      IF(N3.NE.0) THEN
        L=0
        DO 80 I=N1+N2+1,MR
        DO 80 J=2,K-1
        IF(MPRTN(I,J).EQ.0) GO TO 80
        DO 40 JJ=1,M
40      IWORK(JJ)=MPRTN(I,JJ)
        IWORK(J)=IWORK(J)-1
        IWORK(J+1)=IWORK(J+1)+1
        IF(N2.NE.0.OR.L.NE.0) THEN
          DO 60 II=MR+1,MR+N2+L
          DO 50 JJ=1,M-1
50        IF(MPRTN(II,JJ).NE.IWORK(JJ)) GO TO 60
          IF(MPRTN(II,M).EQ.IWORK(M)) GO TO 80
60        CONTINUE
        END IF
        L=L+1
        DO 70 JJ=1,M
70      MPRTN(MR+N2+L,JJ)=IWORK(JJ)
80      CONTINUE
      END IF
```

```
      DO 90 II=1,MR
90    MPRTN(II,1)=MPRTN(II,1)+1
      N1=M1
      N3=N2+L
      N2=MR-N1
      M1=MR
      MR=MR+N3
99    CONTINUE
      RETURN
      END

      INTEGER FUNCTION INX(I,J)
C
C       PICKS OUT THE APPROPRIATE ELEMENT OF A SYMMETRIC
C       MATRIX STORED IN LOWER TRIANGULAR FORM
C
      IF(I.GE.J) THEN
        INX=I*(I-1)/2+J
      ELSE
        INX=J*(J-1)/2+I
      END IF
      RETURN
      END

      INTEGER FUNCTION NFACT(N)
C
C       CALCULATES N FACTORIAL
C
      NFACT=1
      IF(N.LE.1)RETURN
      DO 10 I=2,N
10    NFACT=NFACT*I
      RETURN
      END
```

```
      SUBROUTINE SEP(A,N,ONE,EPS,IFAIL)
C
C       DECOMPOSES A (POSITIVE DEFINITE) INTO LL'
C       (L LOWER TRIANGULAR) AND REPLACES A BY L
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(*)
      ZSQRT(H)=DSQRT(H)
      IFAIL=1
      DO 20 I=1,N
      DO 20 J=I,N
      IJ=INX(J,I)
      R=A(IJ)
      IF(I.NE.1) THEN
        DO 10 K=1,I-1
10      R=R-A(INX(I,K))*A(INX(J,K))
      END IF
      IF(I.EQ.J) THEN
        IF(R.LT.EPS) RETURN
        D=ONE/ZSQRT(R)
      END IF
20    A(IJ)=R*D
      IFAIL=0
      RETURN
      END

      SUBROUTINE LOWINV(A,N,ZERO,ONE,EPS,IFAIL)
C
C       INVERSION (IN PLACE) OF N X N LOWER TRIANGULAR MATRIX
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(*)
      ZABS(H)=DABS(H)
```

```
      IFAIL=1
      DO 20 I=1,N
      R=A(INX(I,I))
      IF(ZABS(R).LT.EPS) RETURN
      D=ONE/R
      DO 20 J=1,I
      IJ=INX(I,J)
      IF(I.NE.J) THEN
        SUM=ZERO
        DO 10 K=J,I-1
10      SUM=SUM+A(INX(I,K))*A(INX(K,J))
        A(IJ)=-SUM*D
      ELSE
        A(IJ)=D
      END IF
20    CONTINUE
      IFAIL=0
      RETURN
      END

      SUBROUTINE MULT1(A,B,C,N,ZERO)
C
C       FINDS C = B'AB (A=A', B LOWER TRIANGULAR)
C       ALL MATRICES N X N
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(*),B(*),C(*)
      DO 20 I=1,N
      DO 20 J=1,I
      IJ=INX(I,J)
      SUM=ZERO
      DO 10 K=I,N
      KI=INX(K,I)
      DO 10 L=J,N
```

```
      LJ=INX(L,J)
      KL=INX(K,L)
10    SUM=SUM+B(KI)*A(KL)*B(LJ)
20    C(IJ)=SUM
      RETURN
      END

      SUBROUTINE MULT2(A,B,C,N,M,NDIM,ZERO)
C
C       FINDS C = B'AB (A=A')
C       A IS N X N, B IS N X M, C IS M X M
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(*),B(NDIM,*),C(*)
      DO 20 I=1,M
      DO 20 J=1,I
      IJ=INX(I,J)
      SUM=ZERO
      DO 10 L=1,N
      DO 10 K=1,N
      KL=INX(K,L)
10    SUM=SUM+B(K,I)*A(KL)*B(L,J)
20    C(IJ)=SUM
      RETURN
      END

      SUBROUTINE NULL1(A,B,N,M,NDIM,ZERO,EPS,IEX)
C
C       CHECKS TO SEE IF AB = 0 (A=A')
C       A IS N X N, B IS N X M
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(*),B(NDIM,*)
      ZABS(H)=DABS(H)
```

```
      IEX=1
      DO 20 K=1,M
      DO 20 I=1,N
      SUM=ZERO
      DO 10 J=1,N
10    SUM=SUM+A(INX(I,J))*B(J,K)
      IF(ZABS(SUM).GT.EPS) RETURN
20    CONTINUE
      IEX=0
      RETURN
      END

      SUBROUTINE NULL2(A,B,N,M,NDIM,ZERO,EPS,IEX)
C
C       CHECKS TO SEE IF B'AB = 0 (A=A')
C       A IS N X N, B IS N X M
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(*),B(NDIM,*)
      ZABS(H)=DABS(H)
      IEX=1
      DO 20 I=1,M
      DO 20 J=1,I
      SUM=ZERO
      DO 10 K=1,N
      DO 10 L=1,N
10    SUM=SUM+B(K,I)*A(INX(K,L))*B(L,J)
      IF(ZABS(SUM).GT.EPS) RETURN
20    CONTINUE
      IEX=0
      RETURN
      END
```

```
      SUBROUTINE EVALUE(A,NDIM,N,RLANDA,P,WMAT,WORK,EPS,
     +IRANK,ZERO,IFAIL)
C
C        FINDS THE RANK, THE EIGENVALUES AND THE
C        EIGENVECTORS OF A POSITIVE SEMIDEFINITE
C        N X N MATRIX A (IN IRANK, RLANDA AND P)
C        NB: USES ROUTINE FROM NAG LIBRARY
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(*),RLANDA(*),WORK(*)
      DIMENSION P(NDIM,*),WMAT(NDIM,*)
      IFAIL=0
      DO 10 I=1,N
      DO 10 J=1,N
10    WMAT(I,J)=A(INX(I,J))
      CALL F02ABF(WMAT,NDIM,N,RLANDA,P,NDIM,WORK,IFAIL)
      IF(IFAIL.NE.0) THEN
        IFAIL=1
        RETURN
      END IF
      IFAIL=2
      IF(RLANDA(1).LT.-EPS) RETURN
      IFAIL=0
      IRANK=N
      DO 20 I=1,N
      IF(RLANDA(I).GT.EPS) RETURN
      RLANDA(I)=ZERO
20    IRANK=IRANK-1
      RETURN
      END
```

```
      SUBROUTINE INTGRL(F,ZERO,EPSABS,EPSREL,RES,ABSERR,W,IW,IFAIL)
C
C        FINDS VALUE OF INTEGRAL FROM ZERO TO INFINITY OF F(X)
C        NB: USES ROUTINE FROM NAG LIBRARY
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION W(2000),IW(252)
      EXTERNAL F
      IONE=1
      IFAIL=0
      CALL D01AMF(F,ZERO,IONE,EPSABS,EPSREL,RES,ABSERR,W,2000,
     +IW,252,IFAIL)
      RETURN
      END
```

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